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NON-CONTACT ACOUSTO-THERMAL SIGNATURES IN AS RECEIVED AND FATIGUE DAMAGED Ti-6Al-4V (POSTPRINT)

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14. ABSTRACT

Interaction of high amplitude acoustic waves with materials produces a small increase in the temperature that can be detected and measured using an IR camera. The changes in temperature as a function of time, due to interaction of high amplitude 20 kHz acoustics, with as received and fatigue damaged polycrystalline Ti-6Al-4V samples are compared. The maximum temperature reached by the sample has been found to increase with increasing fatigue cycles. The role of multiple physical mechanisms, responsible for conversion acoustic energy to heat, like the sample geometry (finite dimension), the microstructure (grain size), and dislocation density are examined. The theoretically evaluated temperature changes are observed to be in reasonable agreement with experimental measurements. The significance of the details of microstructure and dislocation properties needed in theoretical evaluation of temperature changes are used to explain the observed differences between experimental measurements and theoretical calculations.

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Non-Contact Acousto-Thermal Signatures in as Received and Fatigue Damaged Ti-6Al-4V

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Abstract. Interaction of high amplitude acoustic waves with materials produces a small increase in the temperature that can be detected and measured using an IR camera. The changes in temperature as a function of time, due to interaction of high amplitude 20 kHz acoustics, with as received and fatigue damaged polycrystalline Ti-6Al-4V samples are compared. The maximum temperature reached by the sample has been found to increase with increasing fatigue cycles. The role of multiple physical mechanisms, responsible for conversion acoustic energy to heat, like the sample geometry (finite dimension), the microstructure (grain size), and dislocation density are examined. The theoretically evaluated temperature changes are observed to be in reasonable agreement with experimental measurements. The significance of the details of microstructure and dislocation properties needed in theoretical evaluation of temperature changes are used to explain the observed differences between experimental measurements and theoretical calculations.

INTRODUCTION

In the noncontact acousto-thermal NDE method, high amplitude acoustic waves generated by an acoustic horn are propagated across a small air gap to interact with a sample [1]. An infrared (IR) camera is placed across from the horn on the opposite side of the sample, and it captures the temperature changes in the region of acoustic interaction with the sample. The change in temperature measured as a function of time is called as Noncontact Thermo-Acoustic Signature (NCATS). The method has been used to evaluate plastic deformation in Ti-6Al-4V and heat damage in polymer composites. The change in temperature in the sample due to acoustic interaction can be described as,

$$\Delta T = \frac{2\pi f t}{\rho C_p} Q_T^{-1}\left(\frac{\sigma_m^2}{E}\right) \tag{1}$$

where $\Delta T = (T - T_0)$ is the change in temperature, T_0 and T are temperatures respectively before and after acoustic excitation, t is the duration of acoustic excitation, ρ is the density of the sample, C_p is the specific heat, Q_T^{-1} is the total internal friction, σ_m is the maximum stress due to acoustic excitation and E is the young's modulus. Equation (1) shows that the temperature change is due to combination of thermal and elastic properties. In the past Sathish et al [1] and Welter et al [2] used phenomenological arguments based on this relation to interpret the results of their measurements without taking into account the details of the physical mechanisms occurring in the material. This paper emphasizes details of physical mechanisms responsible for temperature changes due to interaction of high amplitude acoustic waves with polycrystalline sample of Ti-6Al-4V subjected to cyclic loading as an application of NCATS method to evaluate evolving fatigue damage. The experimental results of the temperature change are explained based on multiple physical processes occurring in the material. Theoretical description of each of the processes and their contribution to the temperature increase is calculated and compared with experimental measurements.

MATERIALS AND EXPERIMENTAL METHODS

The material used in the experiment is a polycrystalline sample of Ti-6Al-4V with duplex microstructure. It is a dual phase alloy with pure α and a mixed ($\alpha+\beta$). The ($\alpha+\beta$) phase has a lamellar structure with alternating plates of α and β phases. The overall content of α and β phases in the sample is respectively 95% phase and 5% . The crystal structure of the α phase is hexagonal close packed (HCP) while that of β phase is body center cubic (BCC). The average grain size of the sample is 20 μm [3]. The flat dogbone samples used in the experiments have overall dimensions of 150 mm (L) x 30 mm (W) x 2.5 mm (T) with a gage section of 25.4 mm x 12.5 mm x 2.5 mm.

Detailed description of the experimental methods and optimization procedures can be found elsewhere [1] and hence only a short description is provided here for continuity. As shown in Fig.1, the experimental set up consists of an ultrasonic horn operating at 20 kHz to produce high amplitude acoustic signals, an IR camera to detect and measure the temperature, a flat dogbone sample, a servo hydraulic machine that is used to impart fatigue damage to the sample through cyclic loading, and a computer that integrates different instruments and custom software for data collection and analysis. The acoustic horn tip is placed a small distance (100 μm-500 μm) from the flat sample. The IR camera is placed on the opposite side of the sample at a distance of approximately 1 m. The acoustic horn is excited by a signal of 200 ms pulse width; the temperature changes are measured as a function of time for 1 s.

The sample was cyclically loaded in a servo hydraulic machine at 10Hz with a maximum and minimum load of 4kN and 0.4kN respectively. The time-temperature data after excitation of the ultrasonic horn was collected in the undamaged state and after subjecting the sample to cyclic loading in increments of 5000 cycles until the sample fractured. The acoustic displacement due to acoustic excitation by the acoustic horn was measured using an optical fiber sensor to be 10 μm.
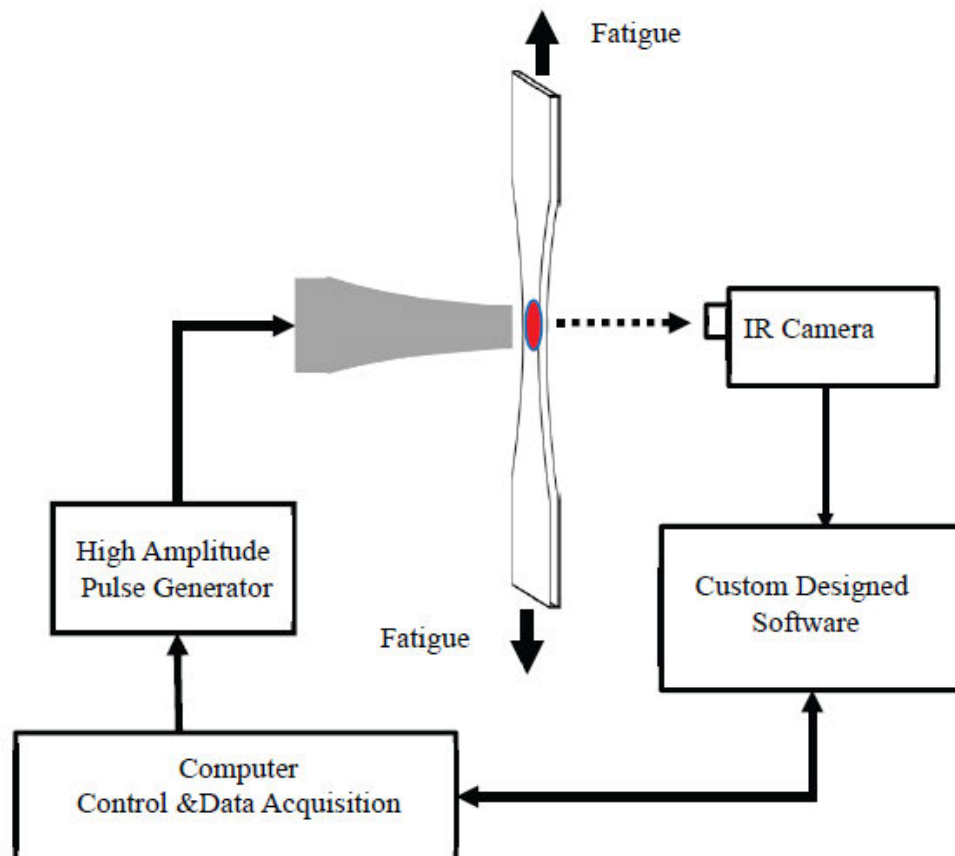

FIGURE 1. Block diagram of the experimental setup used for NCATS measurements.
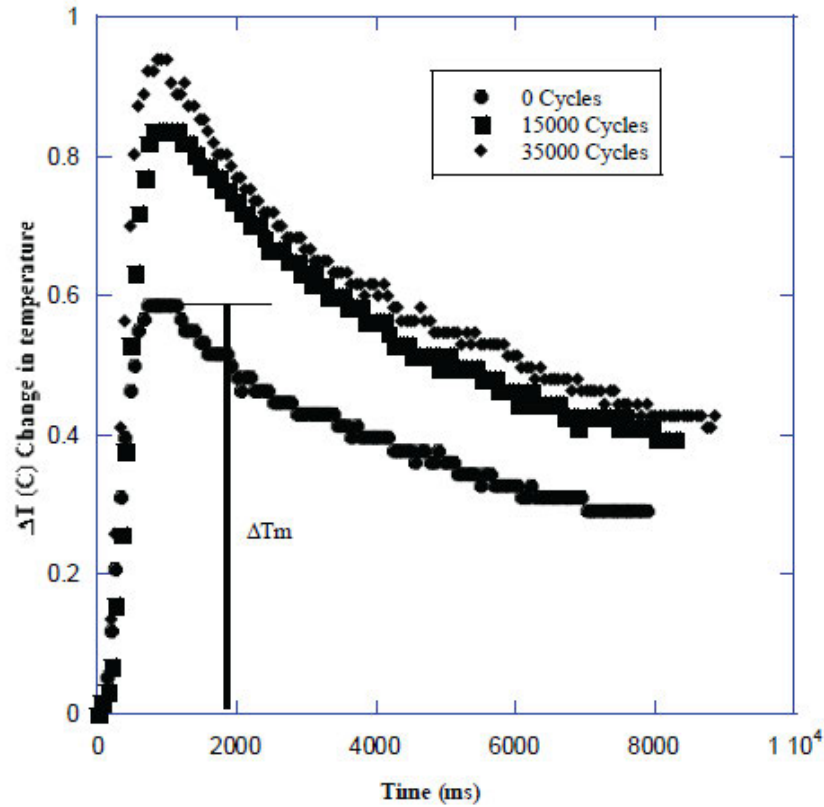
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FIGURE 2. Changes in temperature as a function of time in as received and fatigue damaged sample.

RESULTS AND DISCUSSION

The changes in temperature as a function of time (time-temperature curve or NCATS signature) after the sample is subjected to acoustic excitation in as received condition, after 15000 fatigue cycles, and after 35000 cycles(before failure) are shown in Figure 2. The results show the change in temperature increases rapidly, reaches a maximum and gradually decreases. The maximum temperature reached by the sample ΔT_m and the slope of the curve before reaching maximum increase with increasing number of fatigue cycles. Although different features of the time-temperature curve can be used for the evaluation of fatigue damage, this paper will focus on the most prominent feature of maximum change in temperature (ΔT_m) attained by the sample due to the interaction acoustic waves.

Equation (1) describes the relation between ΔT_m, the elastic and thermal properties, and internal friction of the material. It is well known that the internal friction, Q_T^{-1}, is a function of geometry, grain structure and dislocation structure [4-8]. To understand the maximum change in temperature (ΔT_m) it is necessary to examine each of the internal friction mechanisms. Examination of the experimental configuration (fig 1) shows that it is similar to a vibrating rectangular plate described by Zener [4]. For this configuration, Zener [4] has shown that the internal friction arises due to transverse thermal currents in the sample which is given by eq. (2) and eq.(3),

$$Q_{TTC}^{-1} = \frac{\alpha_t^2 ET}{\rho C_p} \frac{f \cdot f_{TTC}}{f^2 + f_{TTC}^2} \qquad (2)$$

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$$f_{TTC} = \frac{\pi \lambda_{th}}{2h^2 \rho C_P} \tag{3}$$

where α_t is the thermal expansion, λ_{th} (m²s⁻¹) is the thermal diffusivity, and h is the thickness of the sample. Q_{TTC}^{-1} is calculated substituting the physical properties of Ti-6Al-4V [9] in eq. (2), and found to be $5*10^{-8}$. The temperature increase due to Q_{TTC}^{-1} calculated from eq. (1) is approximately 10^{-5} °C, and it is negligible compared to experimental measurements.

Zener [4] has shown that during acoustic wave propagation through polycrystalline material; the elastic deformation is non-uniform leading to non-uniform temperature distribution in individual crystallites due to anisotropic elastic and thermal properties. The non-uniform temperature distribution leads to internal friction and is known as internal friction due to inter-crystalline thermal flow that is expressed as,

$$Q_{ic}^{-1} = \frac{R(3\alpha_t)^2 KT}{\rho C_P} \left[\frac{ff_{ic}}{f^2 + f_{ic}^2} \right]$$

$$\tag{4}$$

$$f_{ic} = \left(\frac{3\pi}{2} \right) \frac{\lambda_{th}}{d^2 \rho C_P}$$

$$\tag{5}$$

where R is anisotropic factor, K is the bulk modulus, and d is the average grain diameter in the sample.

Substituting the physical properties of Ti-6Al-4V and an average grain size of 20 μm in eq (4), the Q_{ic}^{-1} at a frequency of 20 kHz is calculated as $3.4 *10^{-4}$ and the corresponding maximum temperature increase calculated using eq.(1) is 0.08 °C. In samples not subjected to fatigue the internal friction and the corresponding temperature increase is due to combined effect of Q_{TTC}^{-1} and Q_{ic}^{-1}. The total increase in temperature due to the two mechanisms is approximately 0.08 °C and is an order of magnitude smaller than the experimental measurements. The discrepancy can be attributed to uncertainty in the anisotropy of elastic and thermal property of Ti-6Al-4V. Another important factor is the microstructure of the sample. The microstructure of Ti-6Al-4V consists of grains of the α phase, grain of the β phase, and grains of (α+β) phase. The (α+β) grains have lamellar platelet structure with β phase between the platelets of α phase. During acoustic wave propagation the platelets could move against each other producing additional internal friction and heating of the sample. We believe adding contribution from multiple phases and lamellar platelet structure the theoretically calculated temperature change could be comparable to experimental measurements in the sample not subjected to fatigue.

In fatigue damaged samples, the dislocation density is known to increase with increasing number of cycles. It is well known that dislocation motion has a major impact on the mechanical properties and on the internal friction of metallic materials [10]. The internal friction due to dislocation is known depend on the amplitude of the acoustic wave propagating through the material. Granto and Lücke [11,12] developed extensive theoretical models to describe the internal friction due to dislocation that incorporates the properties of dislocations, interaction strength of dislocation and defects and elastic properties of the material. These expressions can be simplified following derivations performed by Bhatia [13] and Mason [14] and assuming the dislocation loop lengths are equal. The simplified expression for dislocation-defect interaction strength [10,11] then becomes,

$$Q_{disl}^{-1} = \left[\frac{16\Lambda}{\pi^5} \right] \left[\frac{\varepsilon_c}{\varepsilon_0} \right]^2 \left[L_N^2 - L_c^2 \right] \tag{6}$$

where Λ is the dislocation density, L_c is the average dislocation loop length, L_N is the average length of dislocation network, ε_c is the dislocation unpinning stress, and ε_0 is the strain due to acoustic excitation.

To calculate the internal friction due to dislocations, Q_{disl}^{-1}, the dislocation density and dislocation loop length in fatigue damaged samples is necessary. This can be obtained from transmission electron microscopy. Maurer [3] has performed dislocation density measurements in Ti-6Al-4V samples subjected to similar fatigue conditions used in the present experiments. The dislocation density was reported to increases from 10^{13} /m² in the as received samples to 10^{15} /m² when the sample failed at 35,000 cycles. It can be assumed that the dislocation densities generated in the present experiments are similar Maurer [3]. To compare theoretical calculations with experimental measurements the

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sample subjected to highest number of fatigue cycles is used. The dislocation density obtained by Maurer [3] is 10^{15} m^{-2} and the dislocation network length in the sample can be assumed not to exceed the average grain diameter of 20 μm. Following Apple et al [15] the average dislocation loop length can be approximated as 1 μm. Substituting all the data into eq.(6), Q_{disl}^{-1} in the sample subjected to 35000 cycles of fatigue is calculated to be 3 10^{-2}, and the corresponding maximum change in temperature from eq. (1) is 2 °C. In fatigue damaged sample, the total internal friction Q_T^{-1} is expressed as,

$$Q_T^{-1} = Q_{TTC}^{-1} + Q_{disl}^{-1} + Q_{ic}^{-1} \tag{7}$$

and using this in eq.(1), the maximum temperature (ΔT_m) is calculated to be approximately 2.1 °C. The experimentally measured ΔT_m is 0.95°C, which is slightly less than the half of the theoretically calculated results. As discussed previously the theoretical calculations of internal friction involve several assumptions and approximations relating to the microstructure of Ti-6Al-4V, dislocation density, dislocation distribution, dislocation loop length, dislocation network length and interaction between point defect and dislocations. In view of all the assumptions, the comparison between experimental measurement and theoretical calculations is reasonable.

SUMMARY

This paper has presented experimental measurement of changes in temperature due to interaction of high amplitude 20 kHz acoustic waves with polycrystalline Ti-6Al-4V sample in as received and fatigue damaged condition. The maximum temperature change (ΔT_m) of the sample due to acoustic interaction has been found to increase with increasing number of fatigue cycles. ΔT_m has been theoretically related to elastic and thermal properties, and internal friction in the sample. This paper has used theoretical models to calculate internal friction due to transverse thermal currents, inter-crystalline thermal flow and dislocations and their contribution to temperature change.

Theoretically determined temperature changes are in reasonable agreement with experimental measurements. Assumptions and simplifications used in theoretical models related to microstructure and dislocation properties are used to explain the observed differences between experimental measurements and theoretical calculations.

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